LATEST RESULTS ON KAON PHYSICS FROM THE NA48 EXPERIMENT

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The NA48 experiment, conceived primarily to look for direct CP violation in neutral kaon decays, has recently published the so far most precise determination of the ε'/ε parameter. After reviewing shortly this result, we report on the 2001 data–taking, which concluded the ε' program by collecting a substantial amount of data with different beam intensity conditions. We also present new precision measurements of the K^0 and η masses and of the $\mathrm{K_S}$ lifetime, that provide consistency checks of our analysis. Finally, the prospects for the future experimental program are discussed.

1 The measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$

The CP–violating two–pion decay of the long–lived neutral kaon, dominated by its CP=+1 component K_1, can also proceed directly in the decay $\mathrm{K}_2 \to \pi\pi$ through the interference of the $\mathrm{K}^0 \to \pi\pi$ amplitudes A_I with isospin I=0 or 2. This direct CP violation is usually parametrized through the quantity

$$\varepsilon' \;=\; \frac{i}{\sqrt{2}} Im\left(\frac{A_2}{A_0}\right) e^{i(\delta_2-\delta_0)} \quad \text{(phase convention: } Im(A_0)\equiv 0) \tag{1}$$

In the Standard Model (SM) picture, ε'/ε is proportional to the CKM parameter $Im(\lambda_t)$ and is expected to be of the order 10^{-3}, though the uncertainty in the calculation is dominated by long distance hadronic contributions (see [1] for a review). Nevertheless, a high–precision measurement of ε'/ε can test the SM prediction against other possibilities, as the Superweak Model (predicting $\varepsilon'=0$) or large contributions from new physics. All experiments performed so far have measured $\mathrm{Re}(\varepsilon'/\varepsilon)$ through the double ratio method [a]:

$$\mathrm{R} = \frac{\Gamma(K^0_L \to \pi^0\pi^0)}{\Gamma(K^0_L \to \pi^+\pi^-)}\frac{\Gamma(K^0_S \to \pi^+\pi^-)}{\Gamma(K^0_S \to \pi^0\pi^0)} \;\simeq\; 1 - 6\times \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$

[a] being the phase of ε' accidentally very close to that of ε ($\simeq -\pi/4$), we get $\varepsilon'/\varepsilon \simeq \mathrm{Re}(\varepsilon'/\varepsilon)$

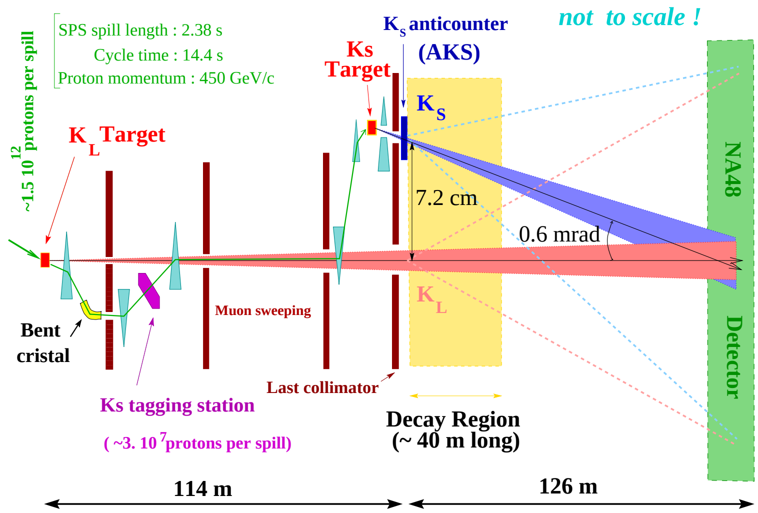

Figure 1: A sketch of the simultaneous $\mathrm{K_L}$ and $\mathrm{K_S}$ beam lines. The fiducial region for K^0 decays begins more than 12 $\mathrm{K_S}$ lifetimes downstream the primary target in order to obtain an almost pure $\mathrm{K_L}$ beam. The $\mathrm{K_S}$ beam is obtained by extracting a small fraction of the protons emerging from the first target and transporting them to a second target located immediately before the decay region. The two beams converge with a small angle in order to be overlapped in the middle of the central detector. Numbers in the figure refer to the 1998/1999 configuration.

exploiting the cancellation of many experimental uncertainties in the ratio. The two dedicated experiments performed during the eighties (NA31 at CERN [2] and E731 at Fermilab [3]) did not reach a definitive conclusion about the occurrence of direct CP violation and a second generation of experiments was needed, which eventually provided a convincing evidence for a non–zero effect after their latest results were announced during 2001:

NA48 at CERN SPS [4]:	$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \ \pm \ 2.6) \times 10^{-4}$
KTEV at FNAL (preliminary) [5]:	$\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \ \pm \ 2.8) \times 10^{-4}$

The method used by NA48 consists in measuring the four decay modes simultaneously from the same fiducial region using two high–intensity and quasi–collinear $\mathrm{K_S}$ and $\mathrm{K_L}$ beams (see figure 1). The two beams illuminate in a very similar way the central detector, based on a large magnetic spectrometer and on a liquid Krypton (LKr) homogeneous calorimeter, where the $\pi^+\pi^-$ and $\pi^0\pi^0$ decays are reconstructed [b]. In order to distinguish $\mathrm{K_S}$ from $\mathrm{K_L}$ events, a $\pm$ 2 ns coincidence is required between the event time and the passage of a proton in a tagging station located along the $\mathrm{K_S}$ beam line. The two main differences between $\mathrm{K_S}$ and $\mathrm{K_L}$ are minimized offline:

- the analysis is performed in 20 kaon energy bins between 70 and 170 GeV to account for the different energy spectra;
- $\mathrm{K_L}$ events are weighted according to the $\mathrm{K_S}$ lifetime to equalize the effective detector illumination from the two beams.

Finally, a set of small (<0.3 % by first principles) corrections have to be applied to account for remaining biases as residual acceptance difference, backgrounds, $\mathrm{K_L} \leftrightarrow \mathrm{K_S}$ mistagging, intensity and reconstruction effects.

2 The 2001 run

The result recently published [4] by NA48 has been obtained from the data collected during the 1998 and 1999 runs, corresponding to 3.3×10^6 $\mathrm{K_L} \to \pi^0\pi^0$ (the decay mode limiting the

[b] for a more detailed description of beam lines and detectors see ([4])

Table 1: Corrections and errors on the double ratio for the 1998+1999 data, listed in decreasing uncertainty.

Statistical error	–	$\pm$ 0.00101	
$\pi^0\pi^0$ reconstruction	–	$\pm$ 0.00058	
Acceptance	+0.00267	$\pm$ 0.00057	
$\pi^+\pi^-$ trigger inefficiency	−0.00036	$\pm$ 0.00052	$\leftarrow$ rate effects
Accidental activity	–	$\pm$ 0.00044	$\leftarrow$ rate effects
Accidental tagging	+0.00083	$\pm$ 0.00034	$\leftarrow$ rate effects
Tagging inefficiency	–	$\pm$ 0.00030	$\leftarrow$ rate effects
Background to $\pi^+\pi^-$	+0.00169	$\pm$ 0.00030	
$\pi^+\pi^-$ reconstruction	+0.00020	$\pm$ 0.00028	
Beam scattering	−0.00096	$\pm$ 0.00020	
Background to $\pi^0\pi^0$	−0.00059	$\pm$ 0.00020	
Long term K_S /KL variations	–	$\pm$ 0.00006	
K_S anticounter inefficiency	+0.00011	$\pm$ 0.00004	
Total systematic	+0.00359	$\pm$ 0.000126	

statistical accuracy). The 2000 run was used to perform some cross-checks and other physics measurements on neutral decay modes, the spectrometer being unavailable after that all its four drift chambers were damaged in an accident occurred in November 1999. Meanwhile, the chambers were rebuilt and reinstalled in time for the 2001 data–taking.

The systematic corrections on the double ratio for the 1998/1999 analysis are listed in table 1. Several sources of error are related to rate effects, namely the residual differences of instantaneous intensity seen by K_S and K_L events (leading to possible differences in accidental activity and trigger inefficiency) or by neutral and charged events (leading to possible differences in the mistagging probabilities, which depend from the K_S proton rate seen by the reconstructed events). For this reason the 2001 data were taken with different beam conditions: profiting of the possibility to extend the SPS duty cycle after the closure of LEP (5.2/16.8 instead of 2.4/14.4 s), we could decrease the average instantaneous intensity by about 30 % while keeping about the same typical per day event statistics (see figure 2). Concurrently the proton energy was decreased from 450 to 400 GeV.

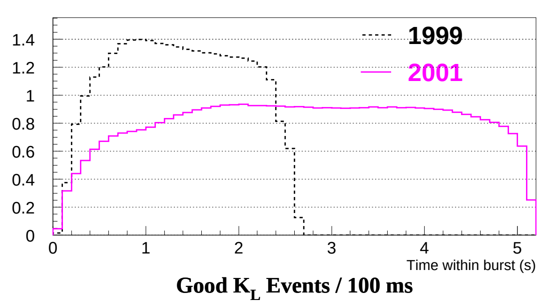

Figure 2: Rate of selected K_L events along the proton burst for the 2001 and 1999 runs

The data–taking was successful, with more than 1.4×10^6 $K_L \to \pi^0\pi^0$ recorded, corresponding to about 14×10^{-4} statistical error on R. This should allow to decrease the final statistical error on $\mathrm{Re}(\varepsilon'/\varepsilon)$ from 1.7×10^{-4} to 1.4×10^{-4}. The performances of the new spectrometer were very similar to the previous runs (about 2.5 MeV/c^2 resolution on the $\pi^+\pi^-$ invariant mass). All the effects related to intensity were reduced as expected: for example, the efficiency of the level–2 charged trigger increased from 98.3% to 99.2% and the probability of an accidental coincidence between a K_L event and a K_S proton was reduced from 10.6% to 8.1%.

We expect that the total error (statistical plus systematic) on the double ratio from these data will be comparable to the published result, so that the 2001 run will be a major cross-check of the $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement against intensity effects.

3 Neutral energy scale and the masses of K^0 and η

The longitudinal decay position for $\mathrm{K}^0 \to \pi^0\pi^0 \to 4\gamma$ is reconstructed by imposing the K^0 mass to the four detected photons, whose transverse positions and energies are precisely measured by mean of the LKr calorimeter. Thus, the global calorimeter energy scale fixes the longitudinal distance scale for the neutral mode, that must be identical to the scale for the charged mode (fixed by the spectrometer geometry). In order not to be too sensitive to the uncertainty on energy scale, the beginning of the fiducial region is defined by an anticounter on the $\mathrm{K_S}$ beam line. The energy scale is fixed by adjusting the anticounter position reconstructed from the decay vertex distribution (see fig. 3) to its known true position.

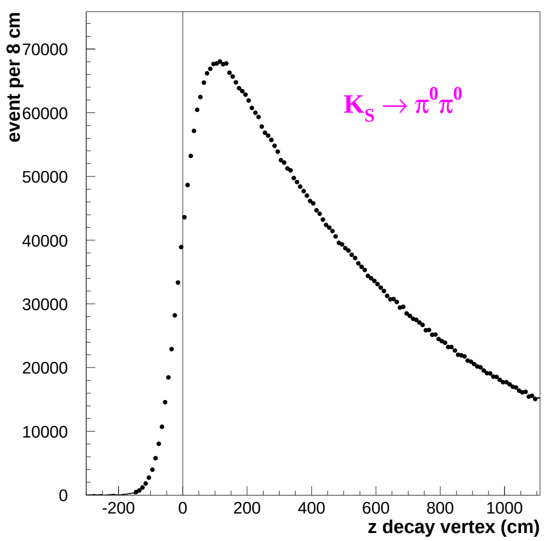

Figure 3: Reconstructed longitudinal vertex position for $\mathrm{K_S}$ neutral decays. An anticounter vetoes all decays occurring upstream the fiducial decay region. The anticounter position can be obtained by fitting the distribution, taking into account the known detector resolution function.

This procedure has been cross-checked by performing all along the data–taking some runs with a special configuration ("η" run): a π^- beam is sent to 2 thin targets placed in known positions within the fiducial region, in order to produce π^0 and η through charge–exchange reaction. Imposing the π^0 or η mass to the reconstructed two–γ decays, the distance between the targets and the calorimeter is reproduced within 3×10^{-4}. This uncertainty on energy scale corresponds to an error of 2×10^{-4} on the double ratio. The value of the η mass used for this check, and the K^0 mass as well, have been measured from the copious data collected in $\mathrm{K_L}$ – only and "η" runs during the 2000 data–taking. To this purpose the $3\pi^0$ decays were used, where the vertex position can be fixed imposing the π^0 mass, which is known with 4×10^{-6} accuracy [6], to the three 2γ pairs. In this way we can measure the ratios M_K/M_{π^0} and M_η/M_{π^0}, which are independent from the energy scale setting. A sample of 128×10^6 $\mathrm{K_L}\to3\pi^0$ and 264×10^3 $\eta\to3\pi^0$ candidates was selected with negligible background. The potentially most dangerous source of systematic error, namely the calorimeter non–linearity, is suppressed with a tight cut on the photon energy asymmetry: $0.7 < 6E_\gamma/E_{tot} < 1.3$
After this cut the systematic error is dominated by other reconstruction effects, such as non–uniformity and uncertainty on the energy sharing among clusters. The mass distribution for the final sample (655×10^3 $\mathrm{K_L}\to3\pi^0$ and 1134 $\eta\to3\pi^0$) is shown in figure 4. Final values are [7]:

$$\begin{aligned} M_{\mathrm{K}^0} &= 497.625 \pm 0.001(stat) \pm 0.003(MC) \pm 0.031(syst)\ \mathrm{MeV/c^2} \\ M_\eta &= 547.843 \pm 0.030(stat) \pm 0.005(MC) \pm 0.041(syst)\ \mathrm{MeV/c^2} \end{aligned}$$

The value for the K^0 mass is in excellent agreement with the PDG 2000 world average [6] and has a similar accuracy, while for the η mass the error of this measurement is three times smaller than the PDG one, and the agreement is poor ($4.3\ \sigma$).

This result is consistent (and independent) with what observed in the "η" run check, where the energy scales reconstructed from $\pi^0\to\gamma\gamma$ and $\eta\to\gamma\gamma$ would differ by 0.1 % if the PDG value of the η mass was used.

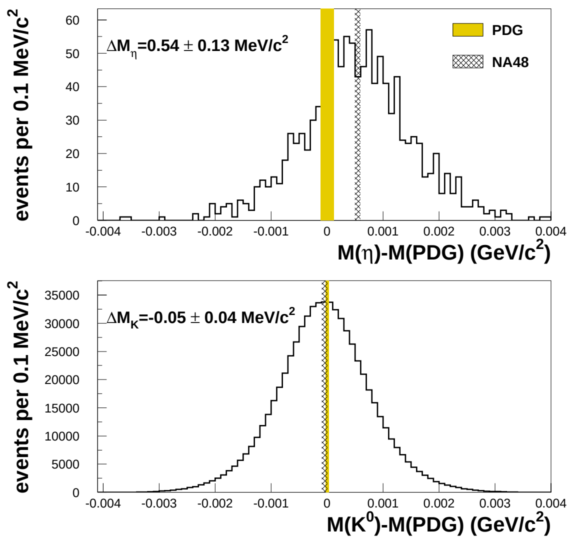

Figure 4: Result for the K^0 and η masses, compared with the PDG values. Shaded areas show the $\pm 1\sigma$ intervals.

4 Measurement of K_S lifetime

Another byproduct of the ε' analysis is the precise measurement of the K_S lifetime. The method consists in fitting the ratio of K_S to K_L lifetime distributions in the same 20 energy bins used in the ε' analysis (fig. 5). In this way the K_L are used to cancel most of the detector acceptance and efficiency effects. Several small ($\lesssim 3 \times 10^{-4}$) residual systematic errors, essentially the same affecting the ε'/ε measurement, have been considered. The measurement can be done independently for charged and neutral events and consistent results [8] are found:

$$\begin{aligned}
\tau_S &= (0.89592 \pm 0.00052\ (\mathrm{stat}) \pm 0.00054(\mathrm{syst})) \times 10^{-10}\ \mathrm{s} \qquad (\pi^+\pi^-) \\
\tau_S &= (0.89626 \pm 0.00129\ (\mathrm{stat}) \pm 0.00100(\mathrm{syst})) \times 10^{-10}\ \mathrm{s} \qquad (\pi^0\pi^0) \\
\tau_S &= (0.89598 \pm 0.00048\ (\mathrm{stat}) \pm 0.00051(\mathrm{syst})) \times 10^{-10}\ \mathrm{s} \qquad (\mathit{combined})
\end{aligned}$$

in good agreement with the preliminary KTEV result [5] and previous measurements (see fig. 6).

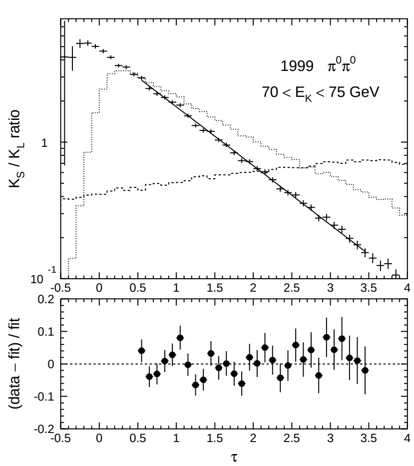

Figure 5: Example of fit for the K_S lifetime. The vertex distribution for K_L and K_S events, as well as the fitted ratio and the fit residuals are shown for $\pi^0\pi^0$ decays in the lowest kaon energy bin (70–75 GeV).

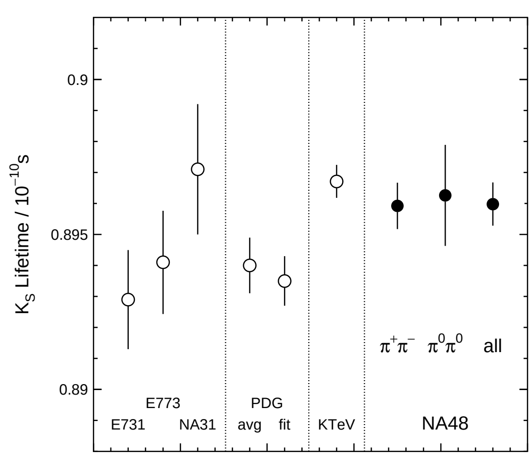

Figure 6: Comparison between this and previous measurements of the K_S lifetime

5 Plans for the next future

The NA48 data can be used to study many K_L , K_S and hyperons rare decay modes. In particular, unprecedented accuracy has been reached on K_S rare decays by running the experiment with a high–intensity K_S beam configuration during the 1999 and 2000 runs. In order to exploit this opportunity a dedicated program (NA48/1) has been approved for the 2002 SPS run. After minor modifications of the beam line and an upgrade of the drift chamber readout, the experiment will be able to run with a K_S beam intensity of 2×10^{10} protons per burst, about 600 times more than the nominal intensity of the ε' runs. The main goals of this project are the possible first observation of the very rare $K_S \to \pi^0 e^+ e^-$ decay (the expected single event sensitivity is 3×10^{-10}) and the study of indirect CP violation in $K_S \to 3\pi^0$.

Another program, devoted to charged kaons (NA48/2), has been approved for 2003. The beam line will be modified in order to have a simultaneous K^+/K^- high–intensity beam and a new beam spectrometer will be installed. The main goal is the possible observation of direct CP violation in charged kaon decays by measuring the K^+/K^- asymmetry in the $K \to 3\pi$ Dalitz plot with accuracy of the order 10^{-4}.

6 Conclusions

The ε'/ε program of NA48 has been completed with the successful 2001 data–taking. The new data will improve the statistical accuracy and perform a major check of the present result:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \ \pm \ 2.6) \times 10^{-4}$$

New precision measurements of the K^0 and η masses and of the K_S lifetime have been obtained as a byproduct of the ε'/ε analysis.

Many other interesting results in kaon physics are being obtained from the collected data, and many more are expected from the future programs, providing quantitative tests of CP violation and low–energy hadron dynamics, highly complementary to B physics.

Acknowledgments

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